Lecture 11: RF Power Amplifiers

- Important components in every wireless system including cordless and cellular telephone, base station equipment, spaceborne, airborne, and ground-based (fixed/mobile) satellite communications, wirelss LAN, etc.
- All these systems require low-cost (high volume) and more reliable solid-state power amplifiers.
- Cordless and cellular phones require low-bias voltage operation (2-5 V), single power supply, very high efficiency (analog version) or high linearity (digital version).
- The cellular phones may require dual- or triple-mode operations including multiple frequencies in both digital and analog versions. The power output is in the range of 0.2-3 W.

Amplifier parameter definitions

- Input and output VSWR
- Power gain: usually the transducer gain, ratio of the power delivered to the load (P_0) to the power available from the source (P_{in}).
- Output power (P_{out}): a strong function of the input power. P_{1dB}
- PAE

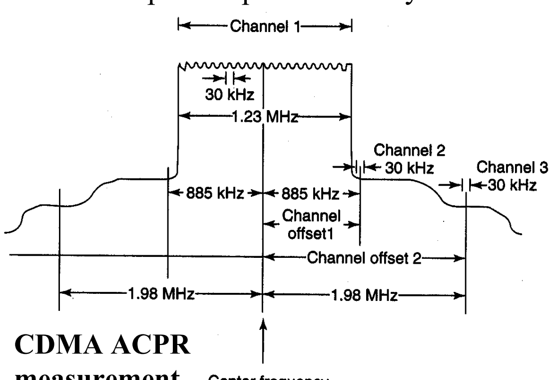
$$\text{PAE} = \frac{\text{output signal power - input signal power}}{\text{dc power}} = \frac{P_{out} - P_{in}}{P_{dc}}$$

$$= \frac{P_{out}}{P_{dc}}\left(1 - \frac{1}{G}\right) = \eta_d\left(1 - \frac{1}{G}\right)$$

Where η_d is known as the drain efficiency. For high-efficiency amplifiers, single-stage gain is required to be on the order of 10 dB or higher.

- Intermodulation distortion: introduced by any nonlinear devices
- ACPR (adjacent channel power ratio)

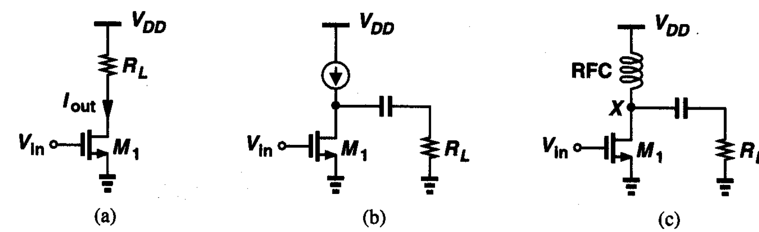
$$\text{ACPR} = \frac{\text{power spectral density in the main channel 1}}{\text{power spectral density in the offset channel 2 or 3}}$$



Commonly used for evaluating the intermodulation distortion performance of RF power amplifiers designed for CDMA or W-CDMA.

CDMA ACPR measurement frequency spectrum.

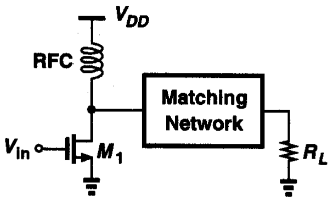
General Considerations:



Consider a transmitter that delivers 1W of power to a 50-Ω antenna

- The peak-to-peak swing, Vpp, at the antenna is then equal to 20V and the peak of the load current is 200 mA.
- The configurations shown in (a) and (b) require a supply voltage greater than Vpp.

- When a RFC is used, the supply voltage can be lowered by a factor of two because Vx can swing from approximately 0 to 2 V_{DD}.
- The RFC approximates a current source that can sustain both positive and negative voltages.
- The maximum Vds experienced by M1 is not relaxed by the use of the RFC.
- A matching network can be interposed between the PA and the load to lower supply voltages.



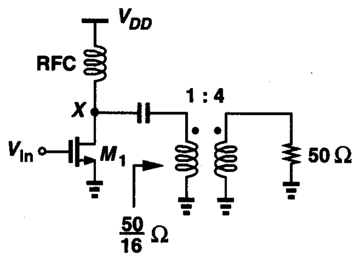
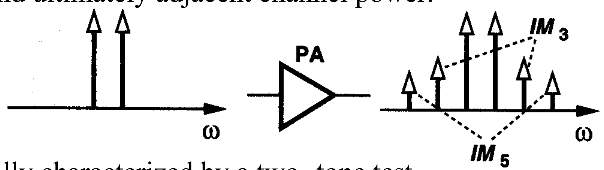


TABLE 9.1 Typical PA performance.

Output Power	+20 to +30 dBm
Efficiency	30% to 60%
IMD	−30 dBc
Supply Voltage	3.8 to 5.8 V
Gain	20 to 30 dB
Output Spurs and Harmonics	−50 to −70 dBc
Power Control	On-Off or 1-dB Steps
Stability Factor	> 1

Linear and nonlinear PAs: linearity of Pas becomes important with certain modulation schemes, e.g., p/4-QPSK

Spectral regrowth and ultimately adjacent channel power.



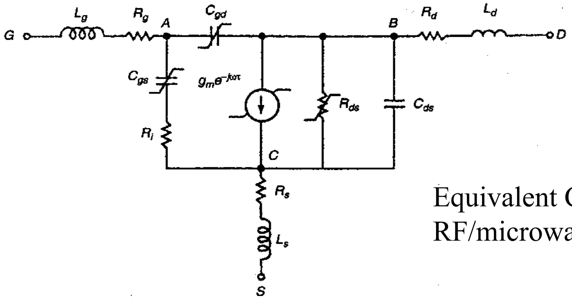
Nonlinearity is usually characterized by a two -tone test.

- Usually operate with the active device displaying some (maybe even gross) nonlinear behavior.
- So a big issue for PA design is the nonlinear device modeling
- The major difference between linear RF amplifiers design and PA design is that, for optimum power, the output of the device (PA) is not presented with the impedance required for a linear conjugate match.
- In the world of PA design, we often struggle to obtain adequate signal gain, as well as extract optimum power from a device. This is an inevitable consequence of cost-driven design; large periphery transistors have lower gain and designers usually are constrained to use the lowest cost technology.

Device Models: Linear and Nonlinear

- An essential part of CAD tools
- Reduced design cycle time and possible "first-pass" design
- Most common method of model development is to measure DC and S-parameters.
- Model extractions are carried out to replicate the measured S-parameters

Linear Device Model

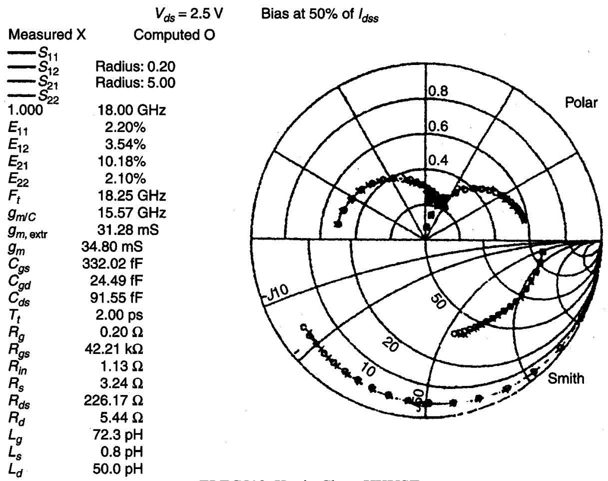


Equivalent Circuit of an RF/microwave transistor

• Cgs, Cgd, g_m and Rds are a strong function of device bias conditions.

• At given bias, this model describes basic linear operation of a FET and the model reproduces the small-signal RF terminal characteristics of the device with good accuracy.

Typical small-signal model parameters for 300-mm power FET biased at Vds = 2.5 V, Ids = 50% Idss



Disadvantages of the Equivalent-Circuit Model

- Difficult to scale to physical structures
- Frequency independent of circuit elements
- No time dependence feature
- Incoherent limitation to linear circuits

Nonlinear Device Models for CAD

- The PA designer is much more sensitive to some of the shortcomings of widely used CAD models than designers of many other kinds of RF devices.
- So a big issue for PA design is the nonlinear device modeling

• Device models for CAD fall into two categories: physical models (bottom up); curve-fit, or top-down approach.

• Interesting to note: bipolar modeling community has, historically, stuck rigidly to the physical model path, while the available FET models are largely of the top-down type.

• Central issue in modeling an RF power transistor: **scaling**

• Almost always, the detailed modeling and curve fitting are done on a small periphery sample device and may be quite accurate.

- The PA designer has to take the small cell and scale it by tens, even hundreds, to "build" a power transistor.
- Such a scaling, unfortunately, is not a simple set of electrical nodal connections.
- Secondary phenomena associated with large periphery devices:
  - Nonuniform thermal effects --- against the customary assumptions made about equal currents and voltages across an array of "identical" circuit elements.
  - Multiple parallel connections also can cause mutual coupling between bondwires.
- The most difficult part of the scale-up RF power transistor models is the difficulty of putting the model and the device through simple comparative tests.
  - DC I-V curves: curve tracers are too slow for RF power transistors. The measured I-V characteristics usually include the transient junction heating effects, which will not occur to any significant extent during an RF cycle.

  - Pulsed I-V measurement is attracting increasing interests, but the measurement system is expensive --- usually provide I-V data quite different from that obtained using curve tracers --- results in "dispersion"
  - The impedances are typically so low, compared to a 50Ω reference, that even simple linear s-parameter measurement is fraught with calibration problems --- pre-matching --- additional challenging calibration problems in de-embedding the matching networks.

Nonlinear model

- Using the same basic configuration for equivalent circuit. Measurement-based.
- Various models differ in the expressions for the drain current, gate-source and gate-drain capacitances.
- Commonly used representation of the nonlinear FET model

$$I_{ds} = (A_0 + A_1V_1 + A_2V_1^2 + A_3V_1^3)\tanh(\alpha V_{ds})$$

where

$$V_1 = V_{gs}[1 + \beta(V_{dso} - V_{ds})]$$

and

$$C_{gs} = C_{gso} \cdot f(V_{gs}, V_{gd})$$

$$C_{gd} = C_{gdo} \cdot f(V_{gs}, V_{gd})$$

Basic steps in nonlinear equivalent Circuit model extraction

- Extract coefficients for I_{ds} to match with measured I-V data. Important data is near the knee of the curves and breakdown near pinchoff.
- Measure S-parameters, extract small-signal model values and derive coefficients for gate-source and gate-drain capacitances to describe its dependence on gate and drain voltages.
- Validate model by comparing measured and simulated data with 50 ohm input and output for P_{1dB} compression point and power levels for other harmonics. Simulations are generally carried out using harmonic balance analysis.

Summary on Nonlinear Device Modeling

- Equivalent circuit models can be easily integrated into circuit simulators.
- Satisfactory to good for a well-designed circuit, especially for mildly nonlinear applications such as class A power amplifiers not operating in hard saturation.
- Biggest problem: scaling in frequency and bias
- Neglect of domain capacitance and the interdependence of the nonlinear elements, e.g., g_m and gate-source capacitance.
- Any change in device parameters needs another round of modeling extraction and validation.

High-Efficiency Amplifier Modes

- A mobile phone handset PA has to be as efficient as possible to conserve battery power (increase talk time)
- Base stations also have efficiency specifications due to power cooling limitations.

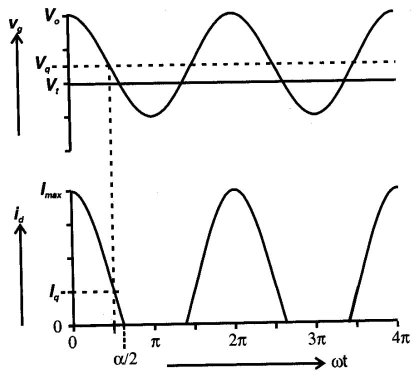
<ins>Definition of conduction angle</ins>

The portion of the RF cycle for which conduction occurs.

V_t: threshold voltage, or cutoff voltage

V_q: normalized quiescent bias point, defined according to $V_t = 0$, $V_0 = 1$.

The required signal voltage amplitude: $Vs = 1 - V_q$



Classification of Power Amplifiers: A, AB, B, C

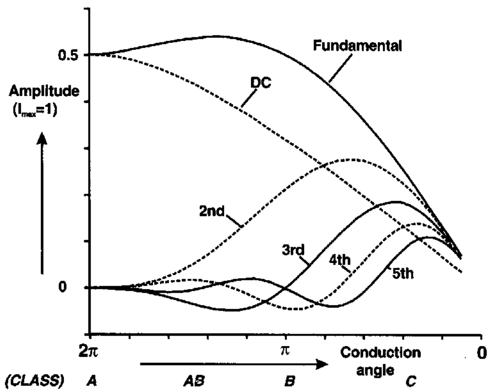
Classical Modes of Operation

Mode	Bias point (Vq)	Quiescent current	Conduction angle
A	0.5	0.5	2π
AB	0–0.5	0–0.5	π–2π
B	0	0	π
C	<0	0	0–π

- The DC component of the output current will decrease as the conduction angle is reduced.
- The variation of the fundamental and other harmonics as a function of the conduction angle can be found by Fourier analysis of the waveforms.

Fourier analysis of reduced conduction angle mode

$$I_{dc} = \frac{I_{\max}}{2\pi}\,\frac{2\sin(\alpha/2) - \alpha\cos(\alpha/2)}{1-\cos(\alpha/2)}$$



$$I_1 = \frac{I_{\max}}{2\pi}\,\frac{\alpha - \sin\alpha}{1-\cos(\alpha/2)}$$

- DC component decreases monotonically as the conduction angle is reduced.
- For the class B condition, $\alpha = \pi$, gives $I_{dc}(\text{class B}) = I_{\max}/\pi$
- Class A gives $I_{dc}(\text{class A}) = I_{\max}/2$

- For the class B condition, $\alpha = \pi$, gives the fundamental component as $$I_1(\text{class B}) = I_{\max}/2$$
  <u>The same as the fundamental component in the class A condition</u>

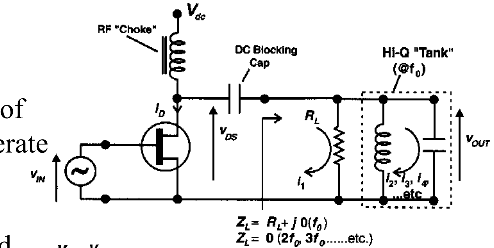
Hint: there appears to be a possibility for decreasing the dc supply power by a factor of $\pi/2$, without changing the RF fundamental component. In other words, the efficiency should increase from 1/2 in the class A mode to $\pi/4$ (about 78.5%) in class B.

To realize the possible higher efficiency, the output termination and voltage waveform have to be considered first.

- The odd harmonics pass through zero at the class B point, but in AB mode, the third harmonic is not negligible.

Circuit analysis for output termination

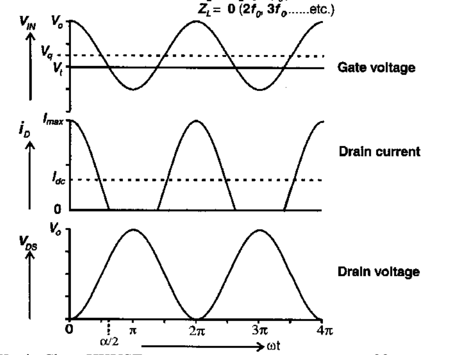
Conceptually, all harmonics of the load are shorted and generate no voltage.



The harmonic short is realized conceptually with a high-Q parallel resonant "tank" circuit at the fundamental.

The RF fundamental output power is given by

$$P_1 = \frac{V_{dc}}{\sqrt{2}} \frac{I_1}{\sqrt{2}}$$

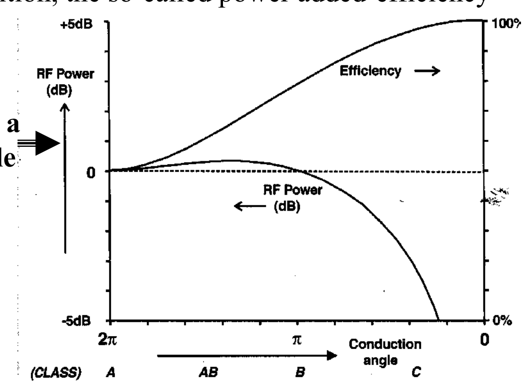


The dc supply power is given by $$P_{dc} = V_{dc} I_{dc}$$

The output efficiency is defined by: $$\eta = \frac{P_1}{P_{dc}}$$

In an RF PA, the RF driver power (input) is quite substantial, which leads to an alternative definition, the so-called power added-efficiency (PAE): $$PAE = \frac{P_1 - P_{IN}}{P_{dc}}$$

RF power and efficiency as a function of conduction angle



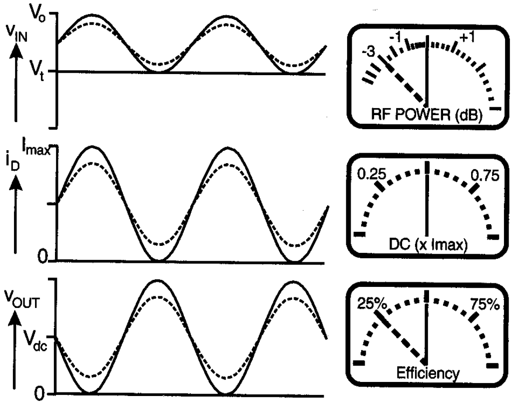
Optimum load and harmonic short assumed

Summary of class A, AB, B, and C PAs

- Between class A and class B operation, the fundamental RF output power is approximately constant, showing an increase of a few tenths of a decibel in the mid-AB range over the class A power output.
- The class B delivers the same power as class A but with a dc supply reduced by a factor of $\pi/2$ compared to class A, giving an ideal efficiency of $\pi/4$.
- The class C condition shows a rapidly increasing efficiency as the conduction angle is reduced to low values; however, that efficiency is accompanied by a substantial reduction in RF output power.

Reduced conduction angle mode analysis: a simple program that computes the necessary Fourier components of the RF current waveforms for a given set of conditions that specify the bias quiescent point and the amplitude of the RF drive signal.

Class A operation



The dotted traces show 3 dB backed-off condition.

Required parameters:

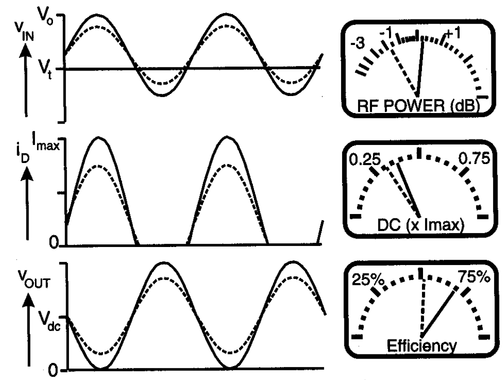
$V_q = 0.5;\ V_s = 0.5$

$V_k = 0;\quad R_L = 1.0$

V_k is a normalized parameter that allows a more realistic turn-on ("knee") transistor characteristics to be included in the analysis. Set to be zero here.

R_L: normalized value of fundamental load resistance, normalized to the optimum class A value of unity.

Class AB operation



If the linear gain starts off below 10 dB, the PAE will start to show a markedly less attractive increase in overall efficiency.

Required parameters:

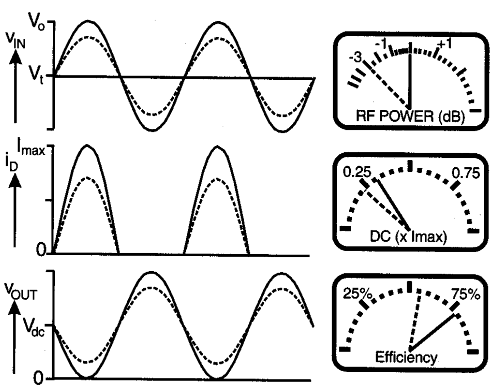
$V_q = 0.25;\ V_s = 0.75$

$V_k = 0;\quad R_L = 0.94$

R_L is reduced from the class A loadline value, reflecting the higher fundamental current component.

Efficiency now increases to 70%, which comes at the expense of drive power: the increase in Vs from 0.5 to 0.75 translates ideally into about 3.5 dB extra drive power.

Class B operation



Use hotter technology (such as GaAs HBT and PHEMT) for cellular phone handsets below 2 GHz, so that we have a higher gain starting point.

Required parameters:

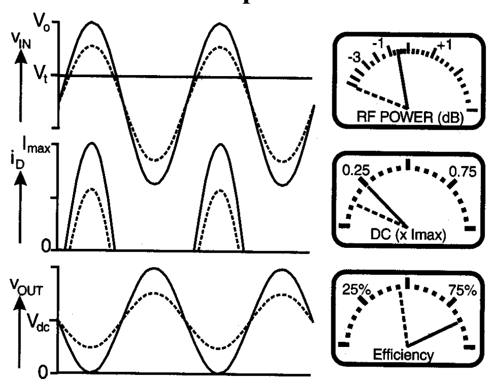
$V_q = 0;\ V_s = 1.0$

$V_k = 0;\quad R_L = 1.0$

The RF power has returned to its original (class A) value. The dc supply is down by a factor of $\pi/2$ and the efficiency has increased to 78.5%.

The downside is that, in theory, 6 dB more drive power is needed --- a large reduction in power gain at RF and microwave frequencies.

Class C operation



The major problem with using class C mode in solid state applications is the large negative swing of input voltage --- reverse breakdown involved.

Required parameters:

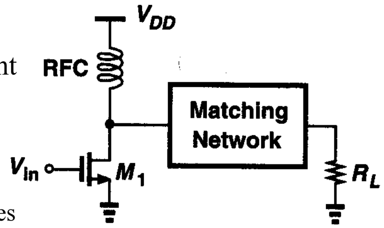
$V_q = -0.5;\ V_s = 1.5$

$V_k = 0;\quad R_L = 1.14$

The current waveform is reduced to a train of short pulses, which have low dc component but also a lower fundamental RF component. Very high efficiency can be obtained, but at the expense of lower RF output power and very heavy input drive requirements.

Switch Mode PAs

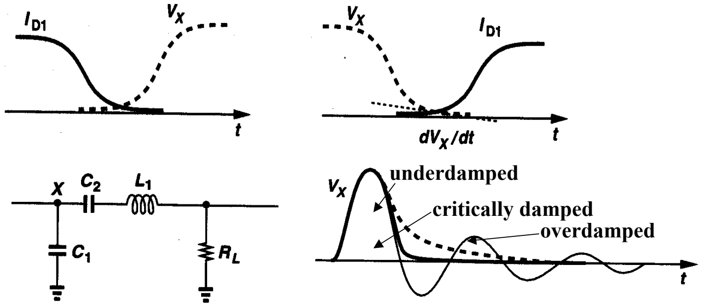
Class E: nonlinear PAs that achieve efficiencies approaching 100% while delivering full power, while delivering full power, a remarkable advantage over class C PAs.



- The transistor operates as a switch, rather than a voltage-dependent current source.
- Requirement for achieving high efficiency
  - M1 sustains a small voltage when it carries current
  - M1 carries a small current when it sustains a finite voltage
  - inevitable transition times between on and off states are minimized.

Class E PAs deal with finite input and output transition times by proper load design.

The components in the load are chosen so that Vx satisfies three conditions:
(1) As the switch turns off, Vx remains low long enough for the current to drop to zero, (2) Vx reaches zero just before the switch turns on, and (3) dVx/dt is also near zero when the switch turns on.



Class E stages exhibit trade-off between efficiency and output harmonic content. Additional filtering can precede the load resistor, but at the cost of power loss in the filter.

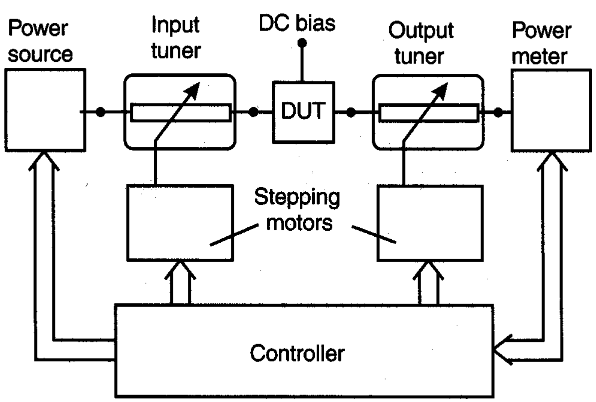
Large peak voltage is required for class E PAs. Usually drain-source has to endure three times of the V_{DD}.

Large-Signal Impedance Matching: load-pull measurement

Commercial load-pull equipment

Both mechanical and electronic tuners have been used in commercial load-pull systems.

Systems with independent fundamental and harmonic tuning are also available.



Typical load-pull configuration

Typical load-pull measurement results

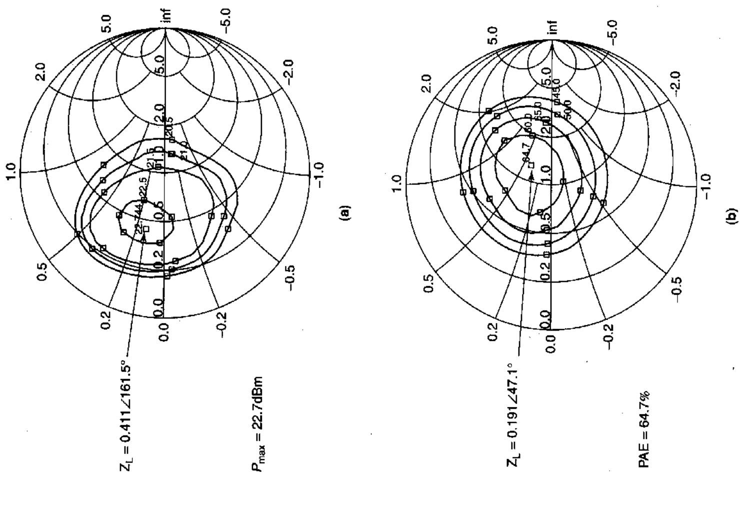


FIGURE 11.18. (a) Measured power loadpull contours using 1 mm FET model, (b) measured PAE loadpull contours using 1 mm FET model @ 1.9 GHz.